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A LABORATORY STUDY OF LOW-FREQUENCY WAVE DISSIPATION DUE TO AN OPPOSING WIND

Final Technical Report
by

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SUMMARY

Estimates of wave dissipation due to an opposing wind based on correlating pressures above the waves with the surface slope were first undertaken by Snyder *et al.*, 1981. These indicated that decay rates due to an opposing wind were roughly an order of magnitude smaller than wind-generated wave growth rates. Other field measurements (Hasselman and Bosenberg, 1991) and laboratory measurements (Young and Sobey, 1985) using this technique have also indicated that dissipation rates are very small.

However, wave dissipation rates can also be derived from measurements of the decline in surface variance with fetch. The measurement of surface variance has been used by Mitsuyasu and Honda, 1982 to estimate the growth rates of laboratory paddle waves due to a concurrent wind. Such measurements are more direct and have consistently yielded higher growth rates than pressure correlation techniques in the air (Bole and Hsu, 1969).

Recent theoretical estimates (Mastenbroek, 1996 and Cohen, 1997) using second-order turbulence closure models anticipate that dissipation rates should be substantially higher than indicated by previous studies.

In this report, we present the results of recent laboratory experiments that provide alternative estimates of wave dissipation due to an opposing wind obtained from measurements of the surface wave field.

These show that the reported levels of dissipation obtained by the technique of measurements in the air are far too low. Furthermore, they show that theoretical estimates also underestimate the dissipation rates by a factor of at least 3.

Further work is required to improve the accuracy of the measurements and to extend the range of wind speeds and wave frequencies investigated.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Theoretical and field studies of wind-wave generation have focussed primarily on the growth phase, that is, with waves travelling in a direction predominantly aligned with the generating wind. A recent review of airflow over waves and wind-wave generation is presented in Belcher and Hunt, 1998.

In coastal regions, offshore winds (opposing the incoming waves) can significantly alter the coastal wave regime. Also, winds changing direction, as in an offshore gust front or the curved wind field and moving core of a tropical cyclone, can create an opposing wind situation thereby modifying the local wave generation regime.

Estimates of wave dissipation based on correlating pressures above the waves with the surface slope were first undertaken by Snyder *et al.*, 1981 and indicated that decay rates due to an opposing wind were roughly an order of magnitude smaller than wind-generated wave growth rates. Other field measurements (Hasselman and Bosenberg, 1991) and laboratory measurements (Young and Sobey, 1985) using this technique have also indicated that dissipation rates are very small.

However, wave dissipation rates can also be derived from measurements of the decline in surface variance with fetch. The measurement of surface variance has been used by Mitsuyasu and Honda, 1982 to estimate the growth rates of laboratory paddle waves due to a concurrent wind. Such measurements are more direct and have consistently yielded higher growth rates than pressure correlation techniques in the air (Bole and Hsu, 1969).

Recent theoretical estimates (Mastenbroek, 1996 and Cohen, 1997) using second-order turbulence closure models anticipate that dissipation rates should be substantially higher than indicated by previous studies.

In this report, we present the results of recent laboratory experiments that provide alternative estimates of wave dissipation due to an opposing wind obtained from measurements of the surface wave field. Its primary objective is to critically review the findings of Young and Sobey (1985) by directly measuring the change in wave energy along a wind-wave tank as undertaken by Bole and Hsu (1967) and Mitsuyasu and Honda (1982).

2. METHOD

2.1 Theory

The local energy density of waves propagating past a point can be evaluated as:

$$E = \rho g \langle \eta^2 \rangle \quad (1)$$

where E is the local energy density, ρ is the density of fluid, g is gravitational acceleration, η is the instantaneous water surface elevation and the angle brackets indicate time-averaging.

Under the action of a following wind, wave energy increases. Mitsuyasu and Honda (1982) used ensemble measurements of surface elevation taken at a sequence of points along a wind-wave tank to derive local wave energy and therefore the increase of wave energy with distance. If a wave does not change its phase speed rapidly with time, we can evaluate the local time-dependent wave growth rate as:

$$\dot{E} = \frac{\partial E}{\partial t} = c_g \frac{\partial E}{\partial x} \quad (2)$$

where c_g is the speed associated with the wave group (and the speed at which energy is propagated by a wave train). For deepwater waves, $c_g = c/2$, where c is the wave speed.

Wave growth rates are usually expressed in a time-based dimensional form as $\gamma = \dot{E}/E$ or as the non-dimensional quantity γ/f where f = wave frequency.

Estimating wave growth and dissipation from spatial changes in wave energy are valid provided that the waves do not break. Once breaking occurs, there is an energy flux from the wave field to subsurface currents and turbulence.

The only difficulty with this technique is that wave fields grow as a spectrum with rapid development of the microscale waves (0.05m<λ<0.4m). Mitsuyasu and Honda (1982) studied the growth of relatively long waves (λ>0.8m) and used spectral filtering techniques to eliminate the higher frequency components.

In this investigation, these techniques have been applied to the case where the wind is in opposition to the propagating waves.

2.2 Wave Facility and Measurement Techniques

These experiments were undertaken in the main wind-wave tank at Water Research Laboratory. Overall tank dimensions are length 30 m, width 0.9 m and height 1.9 m. The layout of this tank is shown in Figure 1.

Waves are generated by a controlled random generator at one end of the tank. During these investigations, only monochromatic waves were investigated. At the far end, a dissipating beach (<2% reflection) has been installed.

The tank is roofed with flow in the air cavity controlled by a large fan fitted at the opposite end to the wave generator. For these investigations, water depth in the tank was 1.45m giving an air cavity depth of 0.45 m. Wind speeds in the air cavity were monitored using a hot wire anemometer mounted from the roof at mid-height within the air cavity.

Total stress measurements are available from the investigations of Cheng and Mitsuyasu, 1992 who undertook experiments in a similar wave tank with an identical air cavity depth. Their measurements showed only minor dependence of the wind stress on the presence, steepness and direction of underlying swell. The stress values are consistent with values assembled by Amorocho and Devries, 1980. The wind speeds investigated by Cheng and Mitsuyasu, 1992 are identical to those used during this investigation and have been adopted for this study.

During this investigation, water surface elevation was monitored using capacitance wave gauges fitted with fine (~200 μm diameter) wire filaments. Each gauge had a range of approximately 200 mm. They were carefully calibrated at the beginning and end of each day of testing by varying the water level in the tank. Six probes were used, five located at distances of 1.5, 4.0, 6.0, 7.5 and 10.0 m from the first probe within the roofed section.

The water surface elevation measurements of the wave probes were recorded at a frequency of 40 Hz per channel by a computer with an analogue to digital converter. These data were stored for subsequent processing.

2.3 Data Processing

Fast Fourier Transforms (FFTs) were used to process 1024 data points from each record (approximately 80s) to determine the local wave energy. Energy from wind waves generated within the tank was filtered from these records by filtering the wave spectra and only integrating energy within a small frequency band in the vicinity of the frequency of the paddle waves (f_p).

A representative spectrum obtained from the wave probe nearest the wave paddle is shown in Figure 2. The vertical scales are shown in both logarithmic and linear forms. The logarithmic ordinate is shown to emphasise the details of the lower energy scales.

The linear ordinate emphasises the higher energy components of the spectrum. Four peaks are clearly defined and have been annotated.

The most important of these is at f_p. This value is the linear wave energy at this frequency. However, smaller peaks can be observed at the second harmonic (annotated) and higher harmonics. This is non-linear wave energy at f_p and reflects the fact that steep waves are slightly non-sinusoidal.

A peak associated with very low frequency motions can be observed at $f=0.047 \approx 0$ Hz. This is primarily associated with seiching in the wind wave tank.

The other major peak is associated with wind-wave generation. At X=0, wind waves generated along the tank achieve a frequency in the vicinity of $f=2$ Hz at wind speeds of 5 and 7 ms^{-1}. These waves continue to propagate along the tank and reflect from the paddle and return down the tank. This wind-wave energy is most evident at X=0 because it has the greatest fetch and wave energy reflected from the paddle decreases with distance because of dissipation by the opposing wind.

It is difficult to distinguish the wind-wave energy from the second and higher harmonics of the paddle waves. Consequently, it has been assumed that all paddle wave energy is restricted to between 0.5 Hz and 1.5 Hz. This may lead to a slight underestimation of the dissipation rates as the harmonic components are more energetic closer to the paddle.

To quantify γ from point measurements of wave energy along the tank, a model of wave dissipation must be fitted to the data. Consistent with previous investigators, we assume exponential dissipation:

$$E = E_0 e^{-2\Delta x} \tag{3}$$

In each case, Δ was determined from the measured data by a least-squares fit of this equation to the measured energy as a function of fetch. Non-dimensional dissipation rates were determined from:

$$\frac{\gamma}{f} = \frac{\dot{E}}{fE} = \frac{c_g}{fE}\frac{\partial E}{\partial x} = -\frac{\Delta c}{2f} \tag{4}$$

3. RESULTS

Measurements have been completed for three paddle wave frequencies and three wind speeds. The test conditions and key results are shown in Table 1.

Table 1. Experiment Results

Test ID	U (ms^{-1})	ω (s^{-1})	$2a_0$ (mm)	ak_0	Δ'_{vis}	Δ_{vis}	$\Delta_{vis,1}$	$\Delta_{vis,2}$	$\overline{\Delta_{vis}}$
990723f/g	5.0	7.85	50.7	0.160	0.003	0.007	0.098	0.069	0.084
990723i/j	7.0	7.85	45.0	0.142	0.003	0.008	0.065	0.084	0.074
990722k/l	5.0	7.39	62.7	0.175	0.004	0.000	0.027	0.045	0.036
990722v/w	7.0	7.39	56.6	0.158	0.004	0.000	0.066	0.045	0.056
990722q/r	5.0	6.28	77.1	0.155	0.003	0.000	0.022	0.012	0.017
990722y/z	7.0	6.28	74.6	0.150	0.003	0.000	0.018	0.030	0.024

The experiment conditions are indicated in the first three columns where U is the wind speed and ω is the wave frequency. The wave height and steepness at the downwind probe are indicated by $2a_0$ and ak_0 respectively. The remaining columns indicate corresponding dissipation rates. Δ'_{vis} is the estimated dissipation rate due to viscous energy dissipation at the surface and the walls of the tank and based on the work of Van Dorn, 1966. Δ_{vis} is the measured dissipation in the absence of the wind. These results indicate that the measurements are sufficient to resolve dissipation rates to an accuracy of better than 0.005.

The quantities $\Delta_{vis,1}$ $\Delta_{vis,2}$ are two independent measurements of the dissipation rate in the presence of wind. Several observations can be made.

The difference between these two values is much greater than the accuracy of measurement of the viscous dissipation rate. This suggests that substantial ensembles will be required to obtain robust measurements in the presence of wind. Differences are as much as 0.03. If we assume that this is twice the standard deviation of populations consisting of 1024 samples, to reduce the error to less than 0.005, ensembles of 36 measurements will be required.

However, the measured wind dissipation rates are far greater than the viscous dissipation rates and these measurements are sufficient for a preliminary assessment of wind dissipation. To do this, the average observed dissipation rate in the presence of wind, $\overline{\Delta_{vis}}$ has been used with the error assigned to half the difference between the individual values.

Figure 3 is a sample graph of a complete set of tank measurements. Wave energy in this figure is expressed as wave height:

$$2a = \sqrt{\frac{8E}{\rho g}} \tag{5}$$

From this graph, it is apparent that the accuracy of the measurement of wave height is approximately ±2mm. This may be a function of probe stability or the ensemble length – means of improving the accuracy of wave measurement are currently being explored. However, as noted earlier, the accuracy of the measurement is sufficient to establish the conclusions of this investigation.

4. DISCUSSION

As discussed in Section 1, wave growth is conventionally reported as a non-dimensional quantity γ/f which is positive for wave growth and negative for wave dissipation. Measurements of wave dissipation are rare in the literature with Young and Sobey, 1985 being the only comparable data set. To provide a context for the measured dissipation rates, these measurements are presented as absolute values that can be compared with measured wave growth rates. When comparing the two sets, it must be acknowledged that wave dissipation commences once the wind velocity falls to a value equal to the wave speed rather than a value of $u_*=0$. The so-called friction velocity, u_*, is defined by:

$$u_* = \frac{\tau}{\rho_{air}} \tag{6}$$

where τ is the total wind stress and ρ_{air} is the density of air.

The format of presentation is that of Plant, 1982 in which γ/f is presented as a function of the ratio of the friction velocity in the air with the wave speed u_*/c. The data of Wu *et al.*, 1979 and Larson and Wright, 1977 have been neglected as recent work (Peirson and Belcher, 1999) indicates that it is inappropriate to use these data sets to assess wind-induced wave growth. The substantial data set of Mitsuyasu and Honda, 1982 has been added as have wind-induced growth rates derived from the data of Banner, 1990 and Banner and Peirson, 1998.

These data are presented in Figure 4 with relevant wave dissipation studies. The summary of the measurement results presented by Young and Sobey, 1985 is shown and lies to the right of all other data. Two theoretical investigations of wave dissipation have been completed recently.

Harris *et al.*, 1995 completed numerical simulations of airflow over a wave travelling in the opposite direction to the wind. The details of the model configuration and characteristic turbulence quantities are not described. They simulated the experiment conditions and found higher phase shifts in the surface pressure distribution than had been measured by Young and Sobey. Their results are also shown in Figure 4 and slightly higher wave dissipation rates are predicted.

Cohen, 1997 has undertaken simulations with a simplified second-order turbulence closure model of wave dissipation due to an opposing wind. This model reproduced the very limited wave dissipation results of the more sophisticated model of Mastenbroek, 1996. Cohen concluded that dissipation rates should be much higher than suggested by Young and Sobey. In Figure 4, Cohen's results show dissipation rates as much as an order of magnitude higher than those of Young and Sobey.

The data from the present investigation has been summarised and presented in an identical form to that above and is also shown in Figure 4. Error bars are shown to express the uncertainty in these measurements. Although the scatter is substantial in this normalisation, it is comparable with the other available measured data sets.

The measured dissipation rates are far higher than has been suggested by previous studies. The closest estimates are those of Cohen, 1997 but the measured values are still a factor of 3 to 10 higher. It is to be noted that a similar disparity exists between measured and numerical estimates of wind-induced wave growth (Belcher and Hunt, 1998).

5. CONCLUSIONS AND RECOMMENDATIONS

The first published measurements of the dissipation of wave energy due to an opposing wind obtained from direct measurement of the surface elevation have been obtained in this study.

These show that the reported levels of dissipation obtained by the technique of measurements in the air are far too low. Furthermore, they show that theoretical estimates also underestimate the dissipation rates by a factor of at least 3.

Further work is required to improve the accuracy of the measurements and to extend the range of wind speeds and wave frequencies investigated.

The methodology developed by Peirson and Belcher, 1999 could also be explored to investigate whether the dissipation rates conform to a normalisation in terms of wave amplitude Reynolds number.

Other studies could be undertaken to investigate the causes of these high dissipation rates, these could include direct measurement of the surface viscous stress at the surface (Peirson, 1997).

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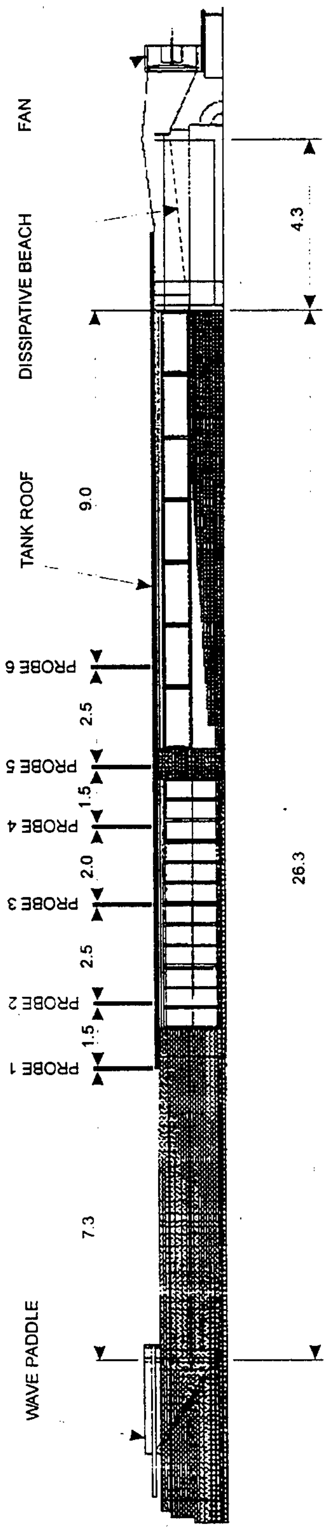
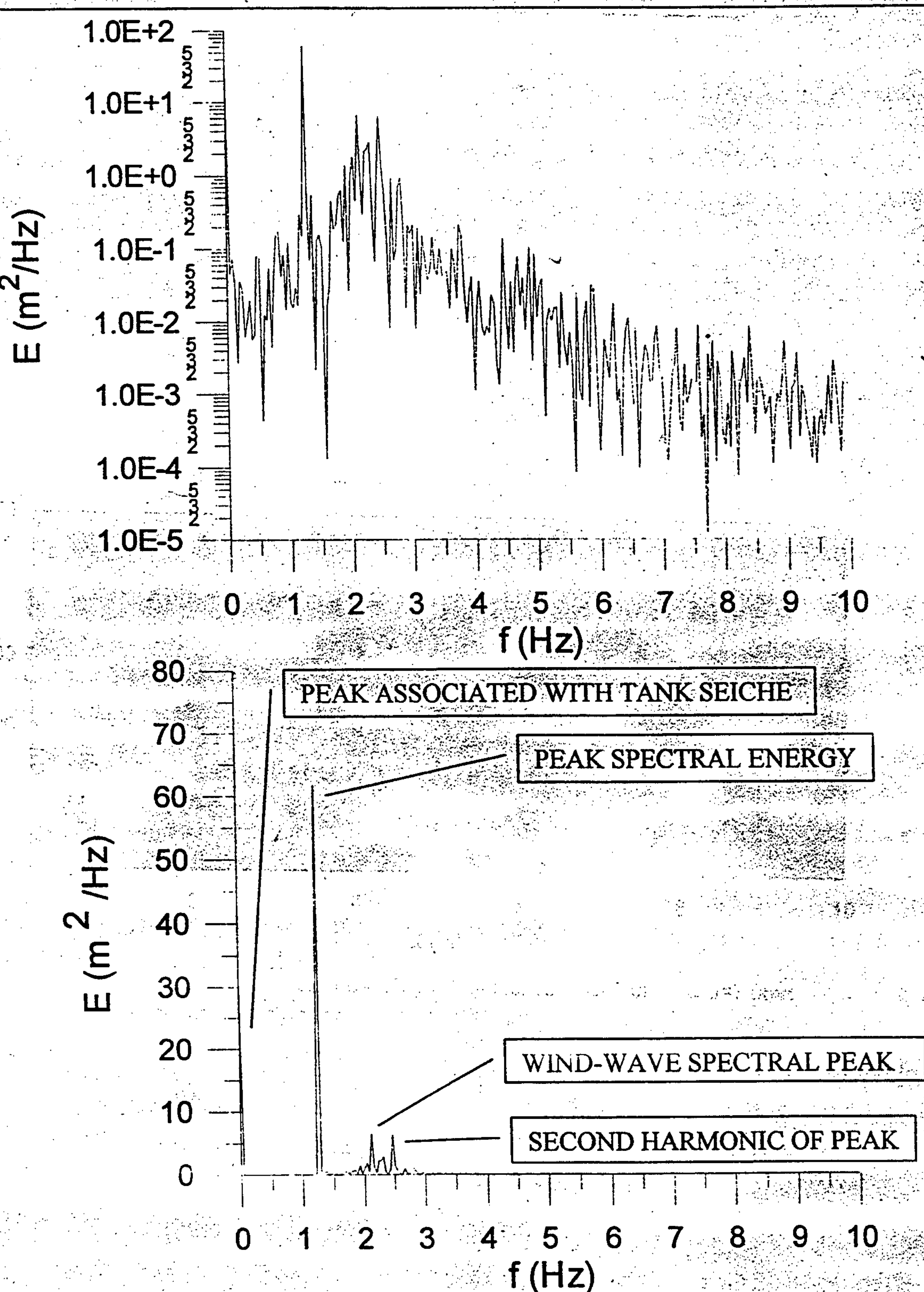
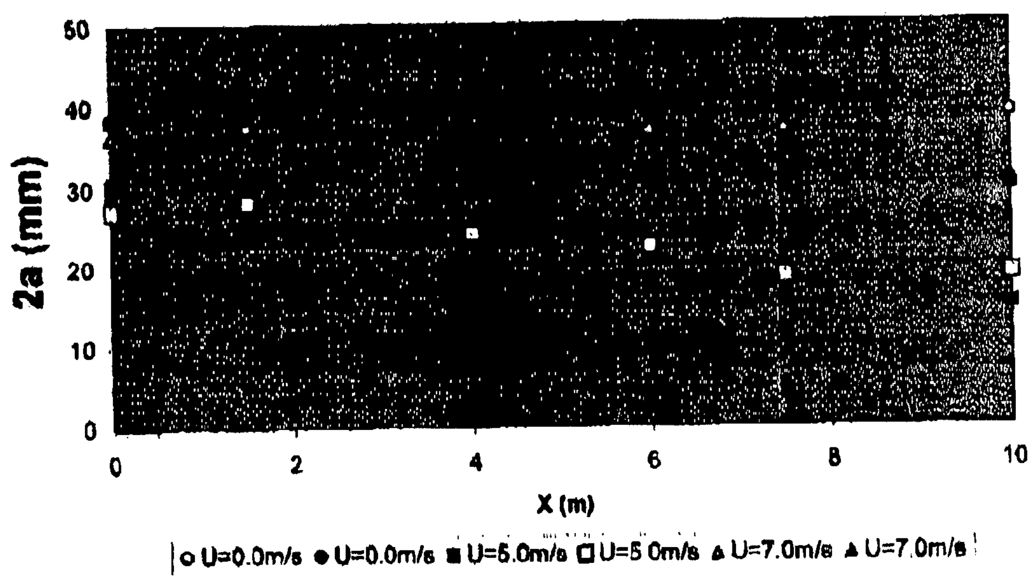


1 METRE FLUME - ELEVATION
DIMENSIONS IN METRES

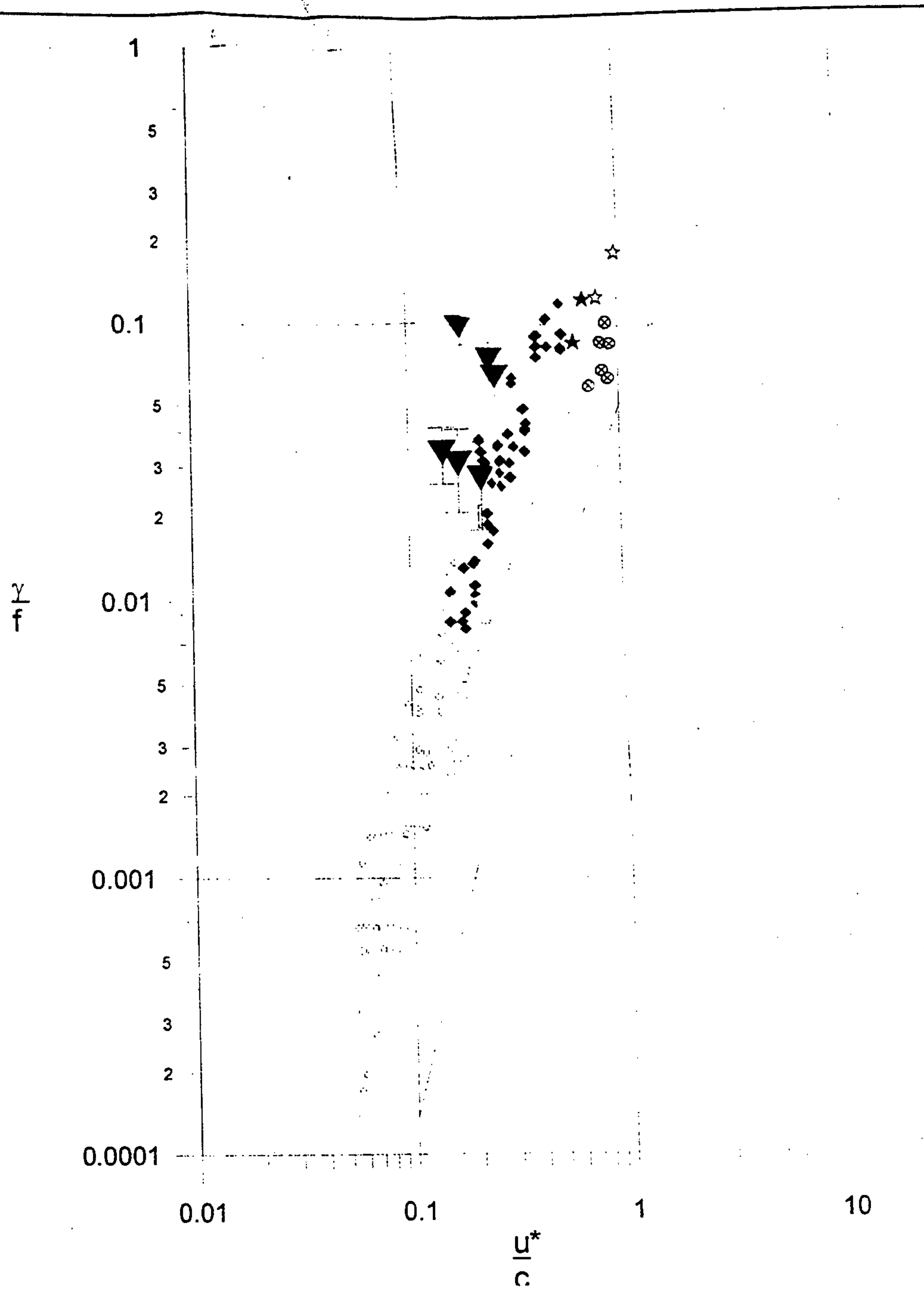
WRL Report No. 203	TANK LAYOUT	Figure 1



WRL Report No. 203	REPRESENTATIVE WAVE SPECTRA AT 0m, WIND SPEED 5 ms^{-1}, f_p=1.25Hz	Figure 2



WRI. Report No. 203	WAVE ENERGY AS A FUNCTION OF PROPAGATION DISTANCE, 1Hz WAVES	Figure 3



Growth rates from Snyder et al. (1981), open circles; Shemdin and Hsu (1967), open triangles; Mitsuyasu and Honda, (1982), solid diamonds; Banner (1990), stars; Mastenbroek *et al.* (1995), crossed square; and Banner and Peirson (1998), crossed circles. Estimated dissipation rates from Young and Sobey (1986) *ak*=0.16, solid line; Harris *et al.*(1995), dotted line; Cohen (1997), dashed line. The measured dissipation rates in this study are shown as solid triangles.

WRL Report No. 203	NON-DIMENSIONAL DISSIPATION RATES COMPARED WITH GROWTH RATES AS A FUNCTION OF INVERSE WAVE AGE.	Figure 4